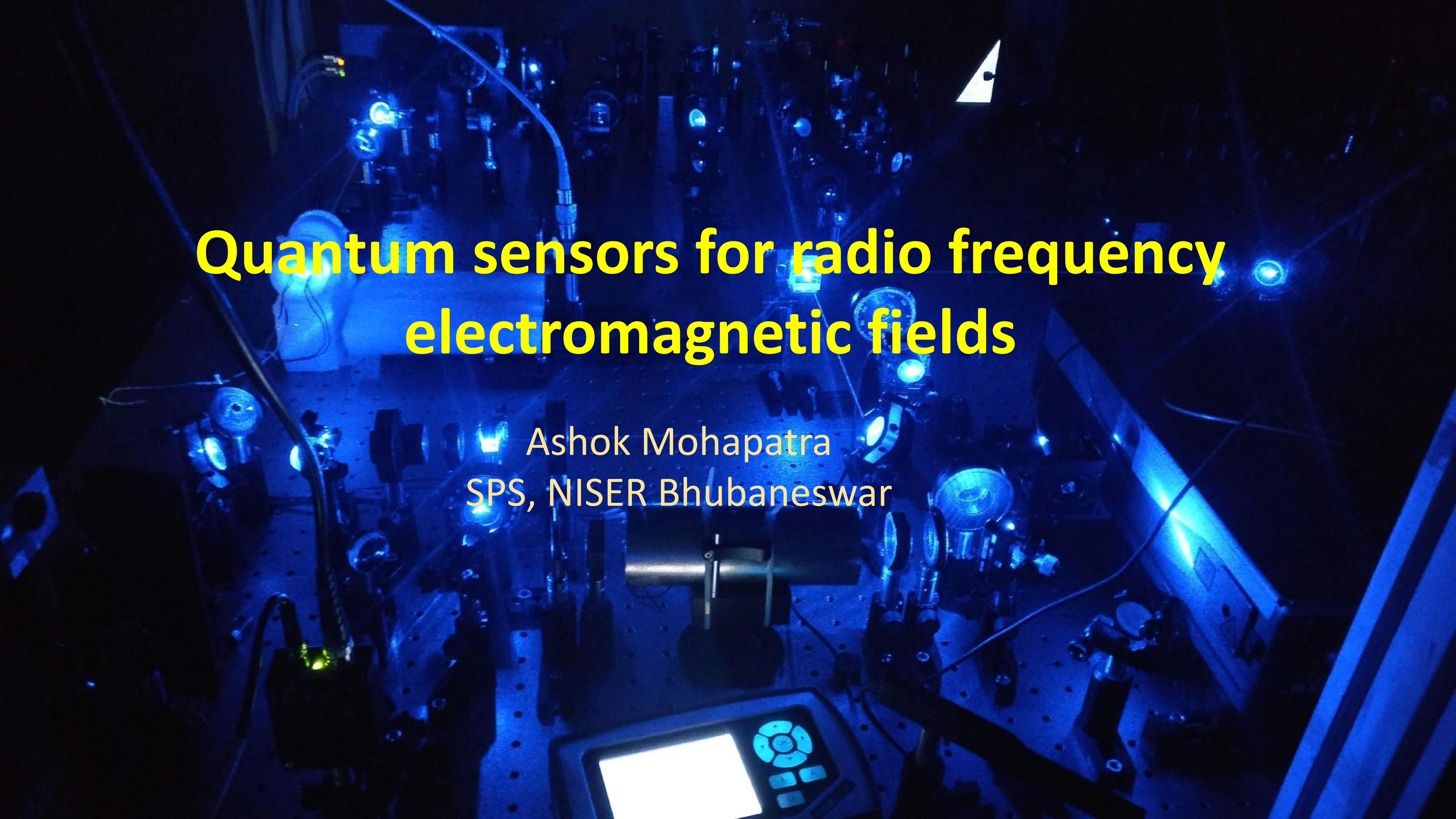


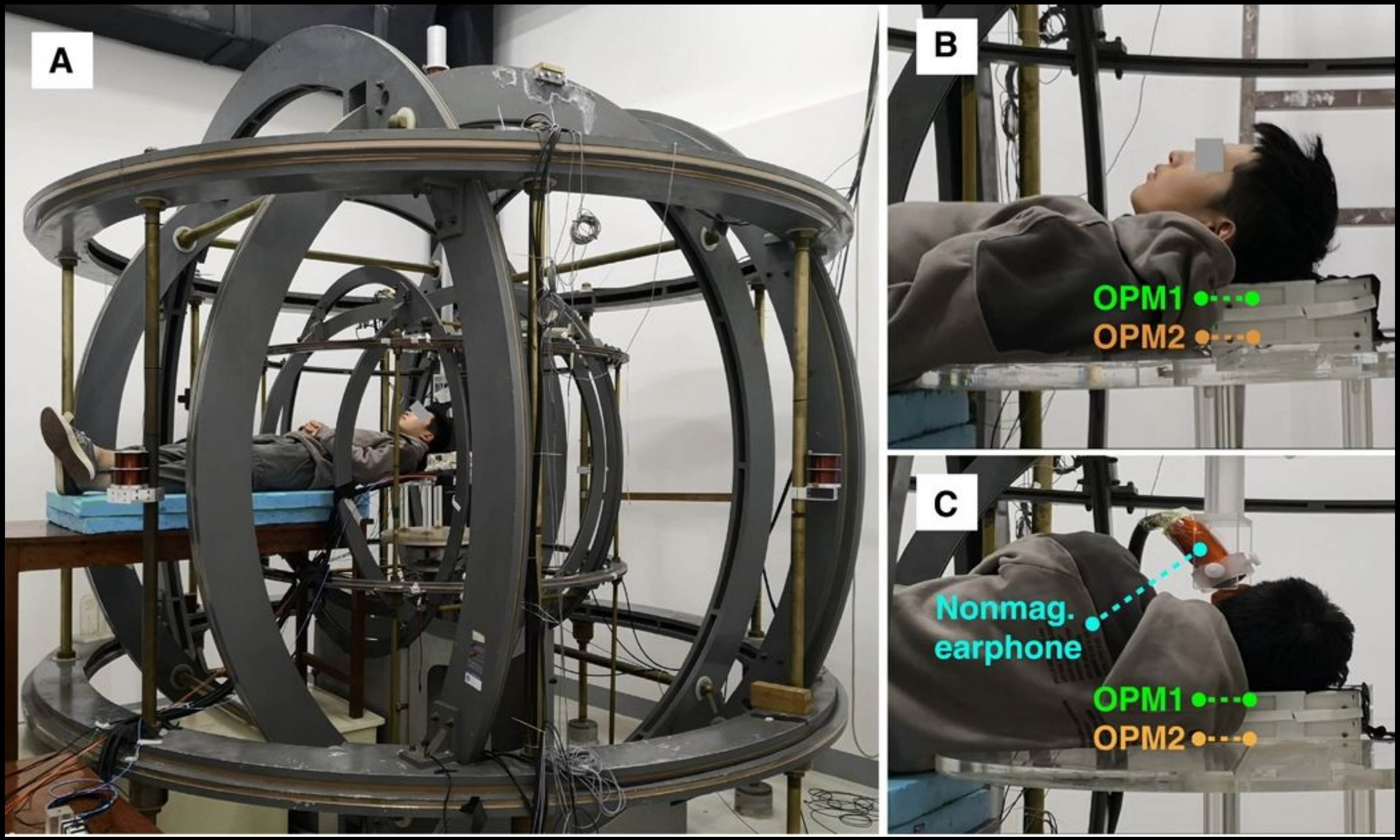
Quantum sensors for radio frequency electromagnetic fields

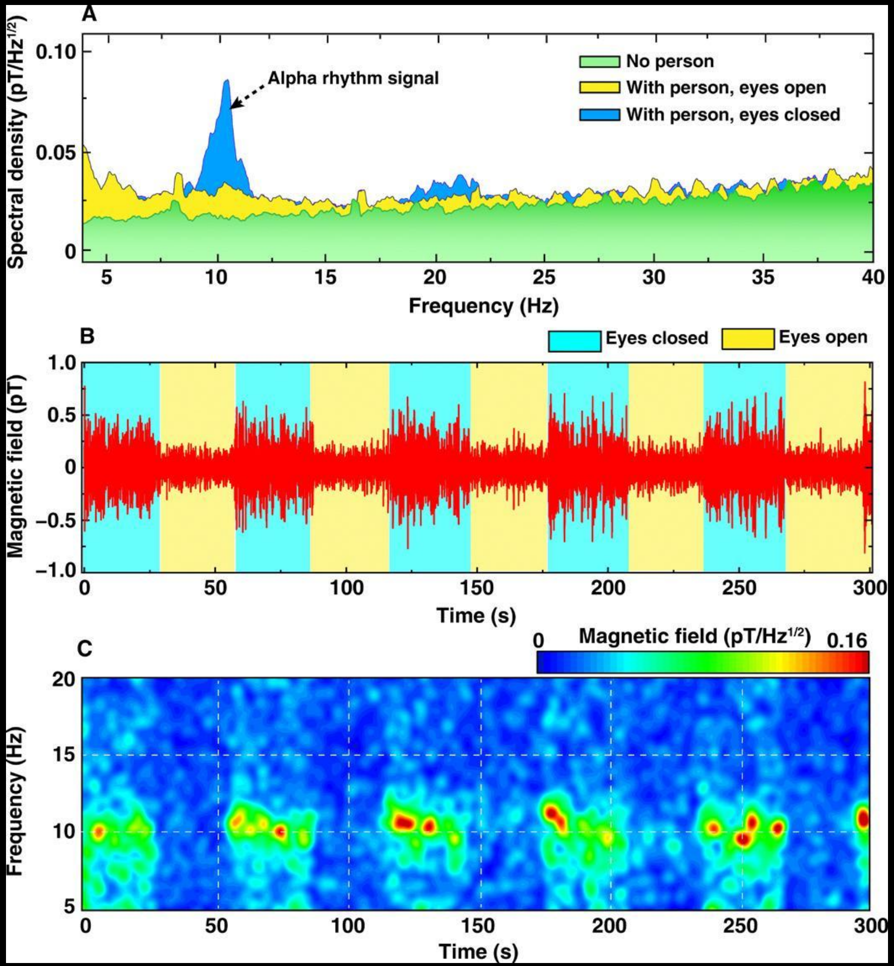
Ashok Mohapatra
SPS, NISER Bhubaneswar

Quantum sensors: applications

- Telecommunications
- Security (Detection of metals)
- Magnetometry in biological systems
  (Non-contact measurements of magnetic fields associated with nerve and muscle activity)
- Geo-magnetic field and magnetic field in sea
- Magnetic field in urban area
  (E.g. a network of GPS synchronized with flux-gate magnetometers 100 pT/Sqrt(Hz) sensitivity was used to study the magnetic environment of city of Berkley)
- Magnetometry in space
  (Atomic vapor based magnetometers are used in spacecraft by NASA to study Planetary and interplanetary exploration)
- Magnetometry at accelerator facilities
  (g-2 experiment at Fermilab to precisely measure the anomalous magnetic moment of muon)
- Fundamental physics
  (Search for axion-induced oscillating electric dipole moment of electron)

Magnetometry in biological system

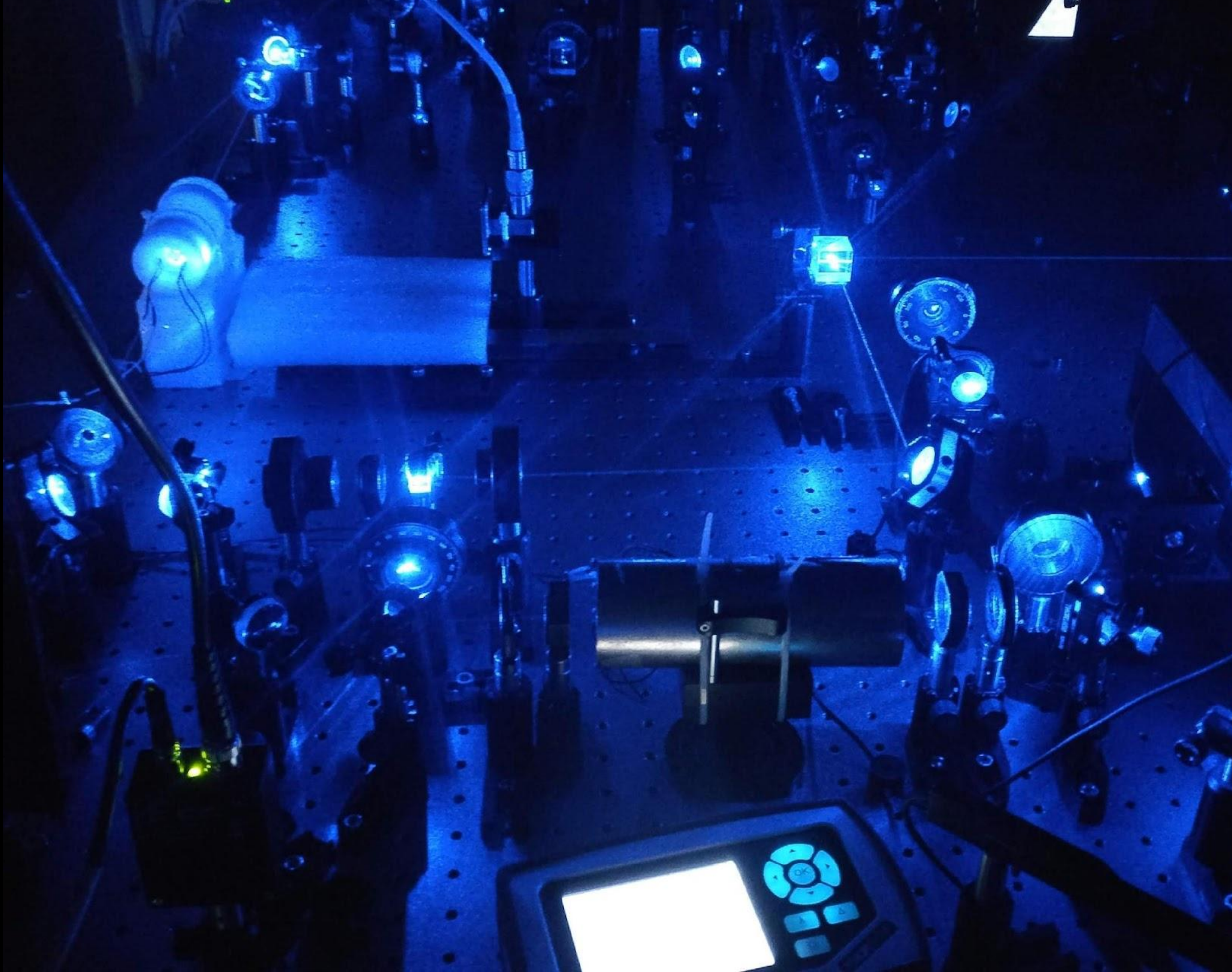




https://www.science.org/doi/epdf/10.1126/sciadv.aba8792

R. Zhang et al. Recording brain activities in unshielded Earth's field with optically pumped atomic magnetometer, Science Advances, **6** : eaba8792 12 June 2020

Electric field sensor



Rydberg atoms

Rydberg states: large *n*

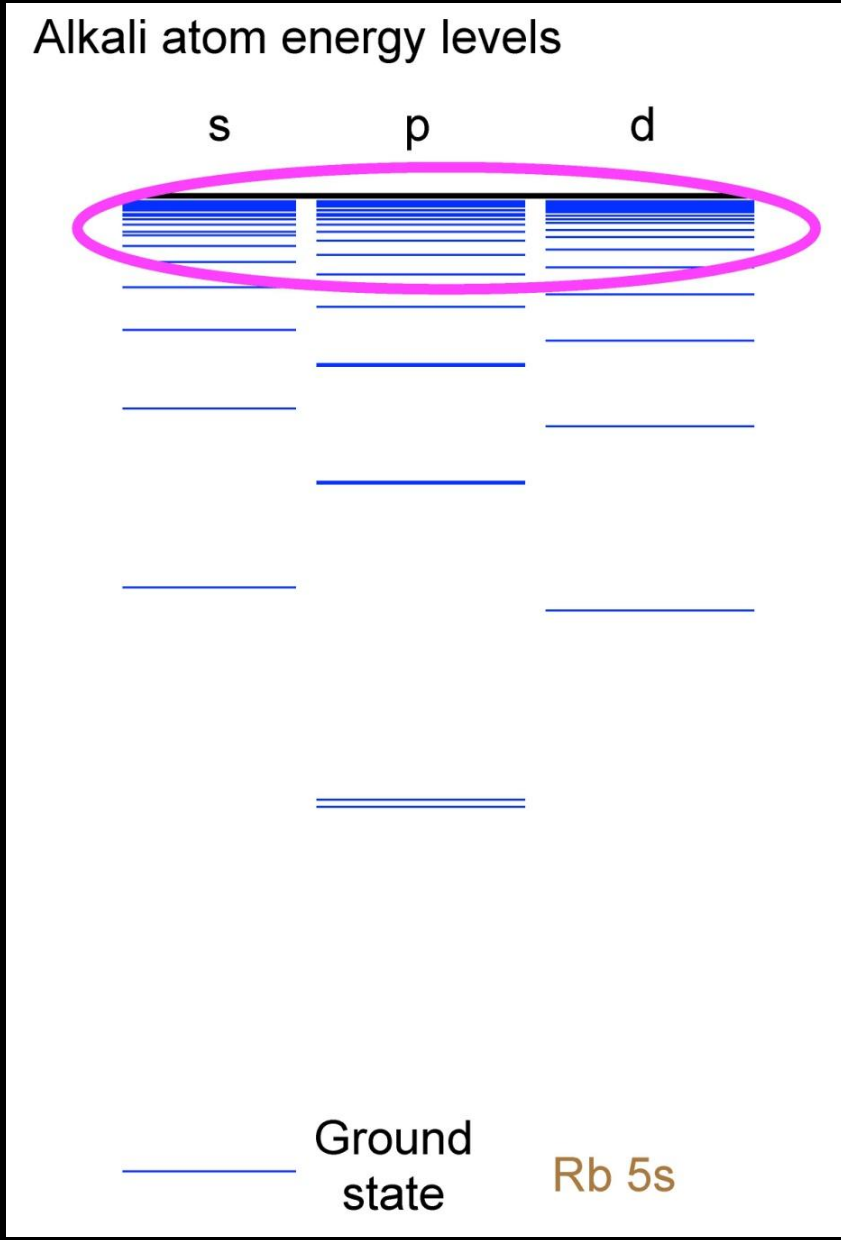
The Rydberg equation is given below.

$$\frac{1}{\lambda} = R_H\left(\frac{1}{n_f^{\,2}} - \frac{1}{n_i^{\,2}}\right)$$

Where, n_f is final state and n_i is initial state.

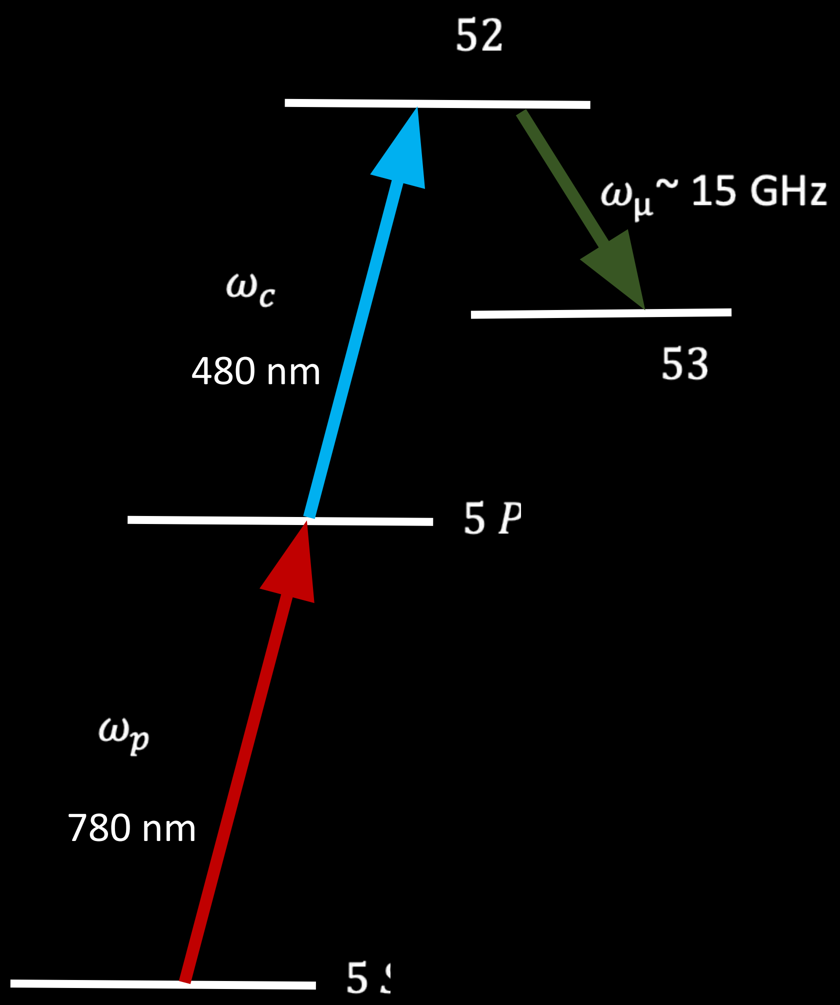
$R_H = 1.097 \times 10^7\ m^{-1}$ = Rydberg constant

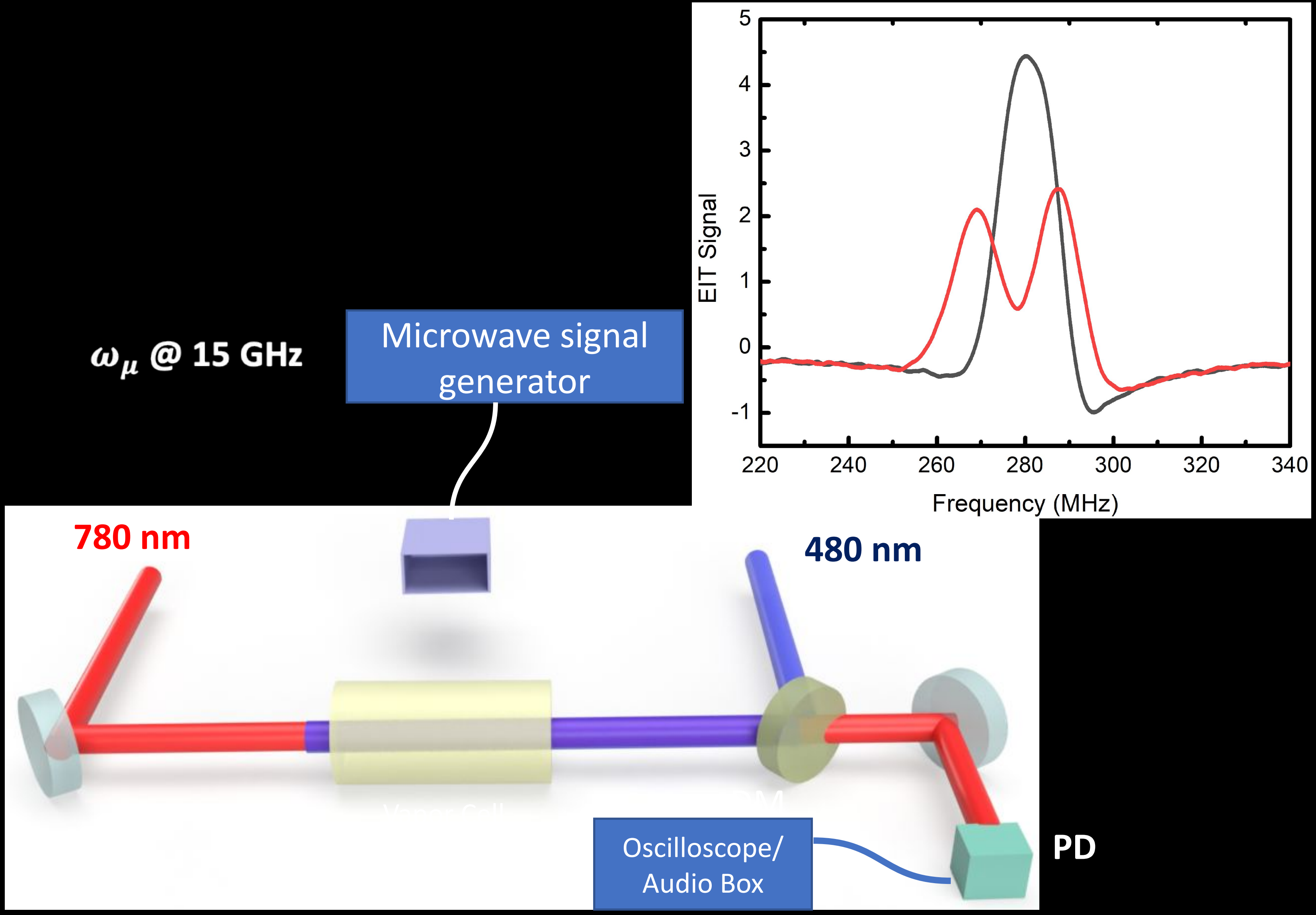
Johannes Rydberg (1854 - 1919)



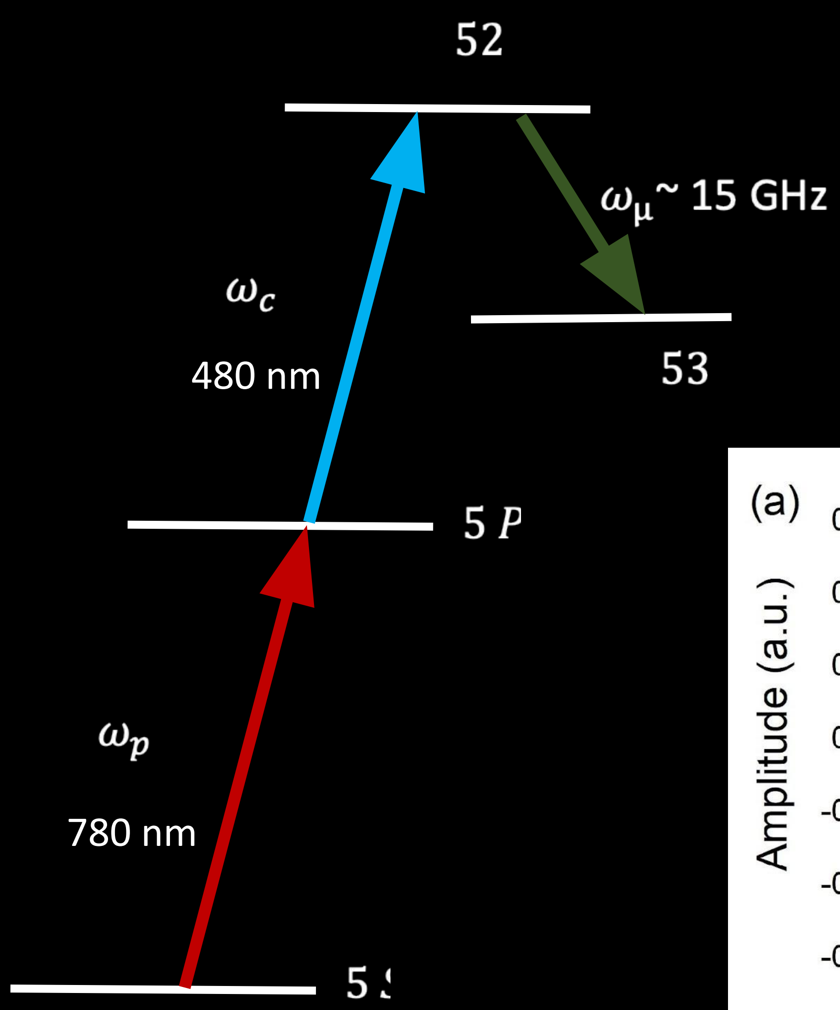
Rydberg atoms as microwave sensor

Rydberg atom sensor for EM radiation (DC - THz): basic principle



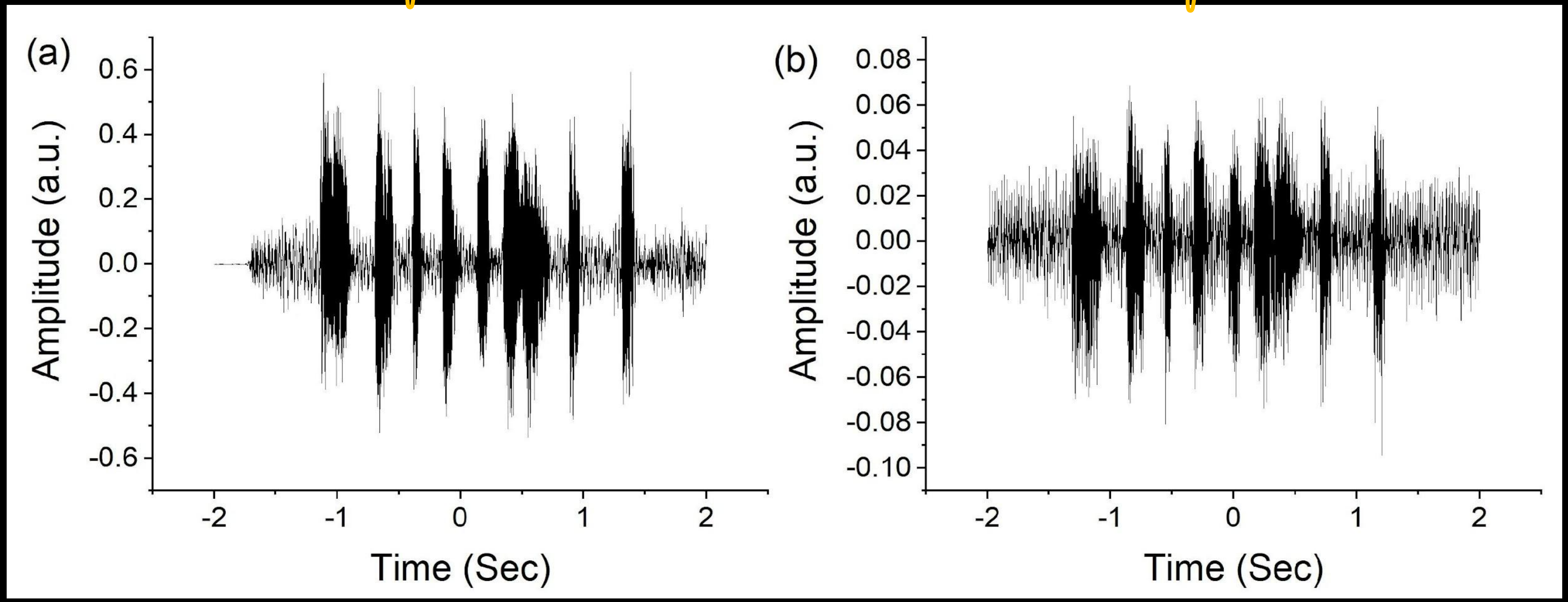


Rydberg atom sensor for EM radiation (DC - THz): basic principle



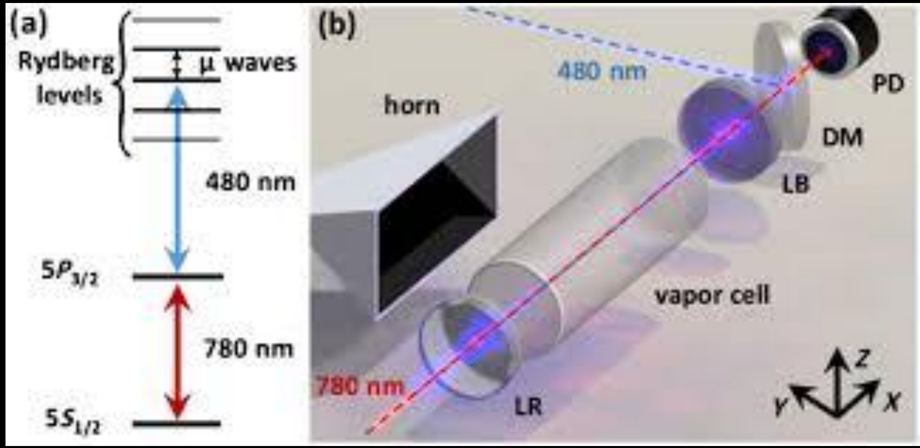
Amplitude modulation of microwave signal

Corresponding intensity modulation of Light detected using a photodiode



Standard antennas with detector Vs. Rydberg atom sensor

V/S



1	Calibration is necessary	Calibration is not necessary
2	Bandwidth of the antenna limited by size	Broadband (Does not depend on the frequency)
3	Metallic structure modifies microwave	Doesn’t modify the microwave field to be detected
4	Issue with accuracy and stability	Accurate, stable, and reproducible
5	It cannot be used as traceable standard	Rydberg atoms can be used as traceable standard

Rydberg atom sensor

PHYSICAL REVIEW APPLIED **15,** 014047 (2021)

Waveguide-Coupled Rydberg Spectrum Analyzer from 0 to 20 GHz

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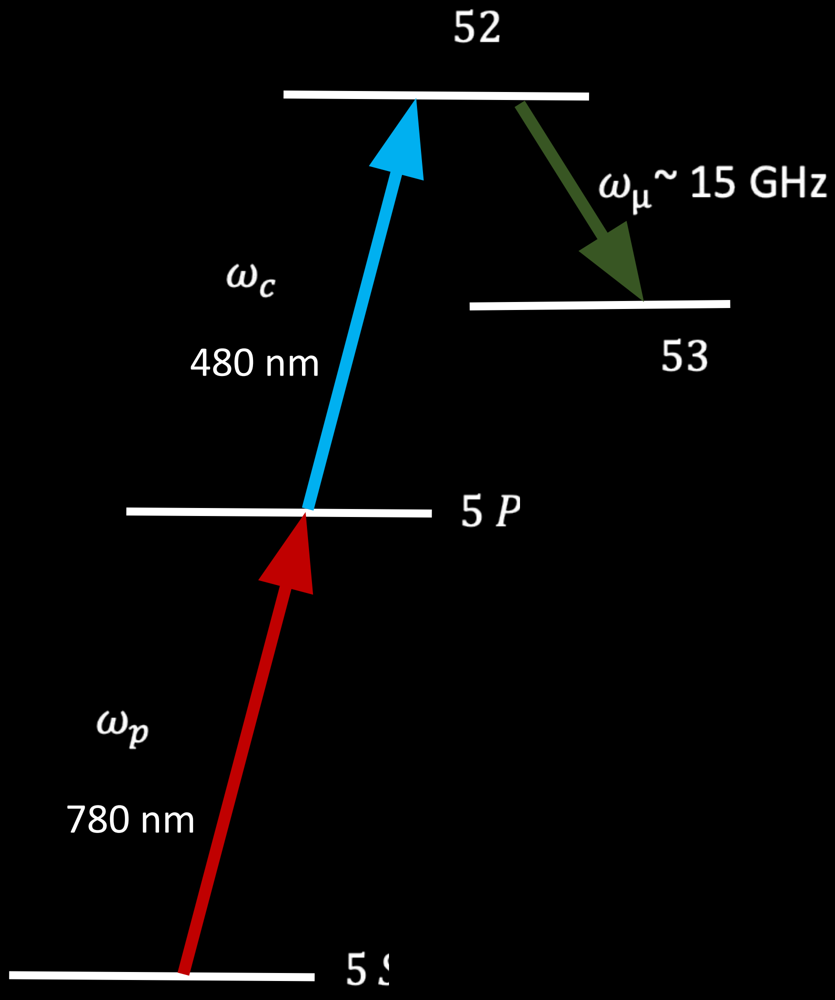
(Received 29 September 2020; revised 10 November 2020; accepted 6 January 2021; published 25 January 2021)

We demonstrate an atomic rf receiver and spectrum analyzer based on thermal Rydberg atoms coupled to a planar microwave waveguide. We use an off-resonant rf heterodyne technique to achieve continuous operation for carrier frequencies ranging from dc to 20 GHz. The system achieves an intrinsic sensitivity of up to −120(2) dBm/Hz, dc coupling, 4-MHz instantaneous bandwidth, and over 80 dB of linear dynamic range. By connecting through a low-noise preamplifier, we demonstrate high-performance spectrum analysis with peak sensitivity of better than −145 dBm/Hz. Attaching a standard rabbit-ears antenna, the spectrum analyzer detects weak ambient signals including FM radio, AM radio, WiFi, and bluetooth. We also demonstrate waveguide-readout of the thermal Rydberg ensemble by nondestructively probing waveguide-atom interactions. The system opens the door for small, room-temperature, ensemble-based Rydberg sensors that surpass the sensitivity, bandwidth, and precision limitations of standard rf sensors, receivers, and analyzers.

- **Sensitivity achieved by standard spectrum analyzer ~ -160 dBm/Hz**
- **Fundamental limit due to thermal noise ~ -171 dBm/Hz**

Rydberg Atom Sensor



WAVEGUIDE-COUPLED RYDBERG SPECTRUM... PHYS. REV. APPLIED **15,** 014047 (2021)

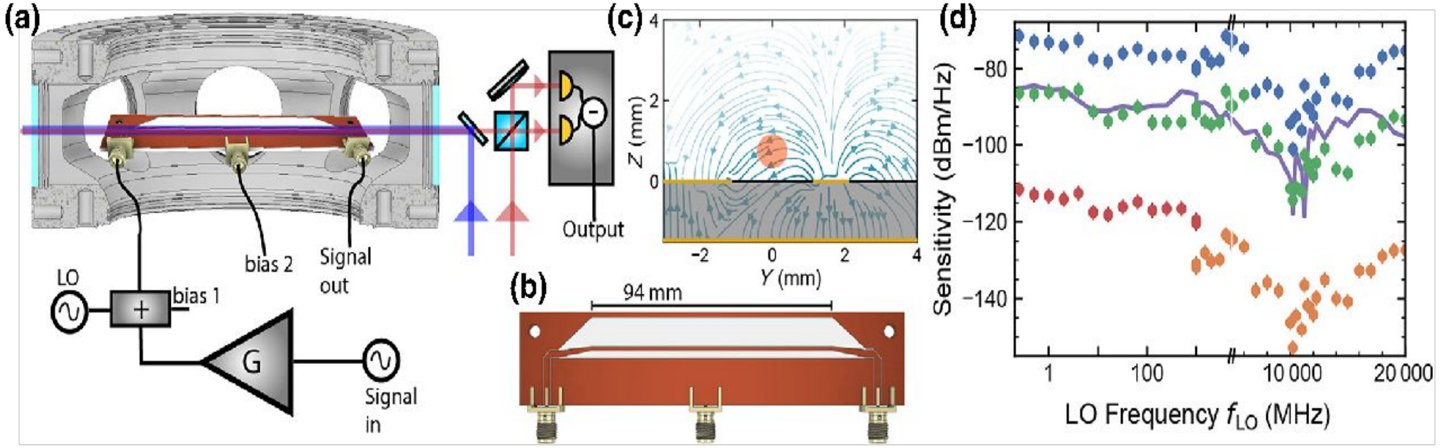
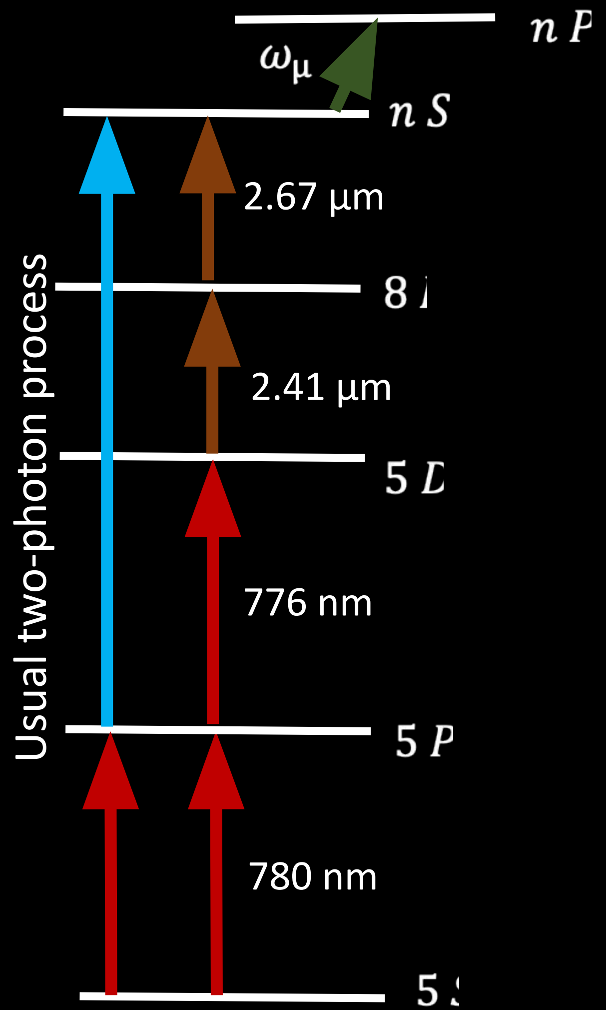


FIG. 1. (a) Simplified experimental setup. Rydberg atoms are detected using a 780-nm and 480-nm beam, counterpropagating above a microwave circuit, with connections for input, output, and dc bias. Signals are detected in homodyne, using a balanced detector. (b) Microwave circuit. A coplanar waveguide transitions to a circuit region where the evanescent electric field area is matched to the Rydberg interrogation area. A third SMA cable, in the center, is used to add a dc bias to the circuit backplane, to help zero ambient dc fields. (c) Field simulations of the microwave circuit along a middle slice of the board. Atoms are interrogated over a 2-mm gap between the signal conductor and ground conductor. (d) Measured sensitivity versus frequency. Directly measured (blue), intrinsic PSN-limited (green), and directly measured using preamplification (red and orange) values are displayed. All error bars represent 2-dB total estimated standard deviation due to known statistical and systematic factors. The theoretically modeled intrinsic sensitivity, with no preamplification, is shown as a purple line. Note that lower and higher frequencies are shown on log and linear scales, respectively.

Four-photon excitation scheme for Rydberg excitation



PHYSICAL REVIEW A **104**, 013711 (2021)

Electromagnetically induced transparency in the strong blockade regime using the four-photon excitation process in thermal rubidium vapor

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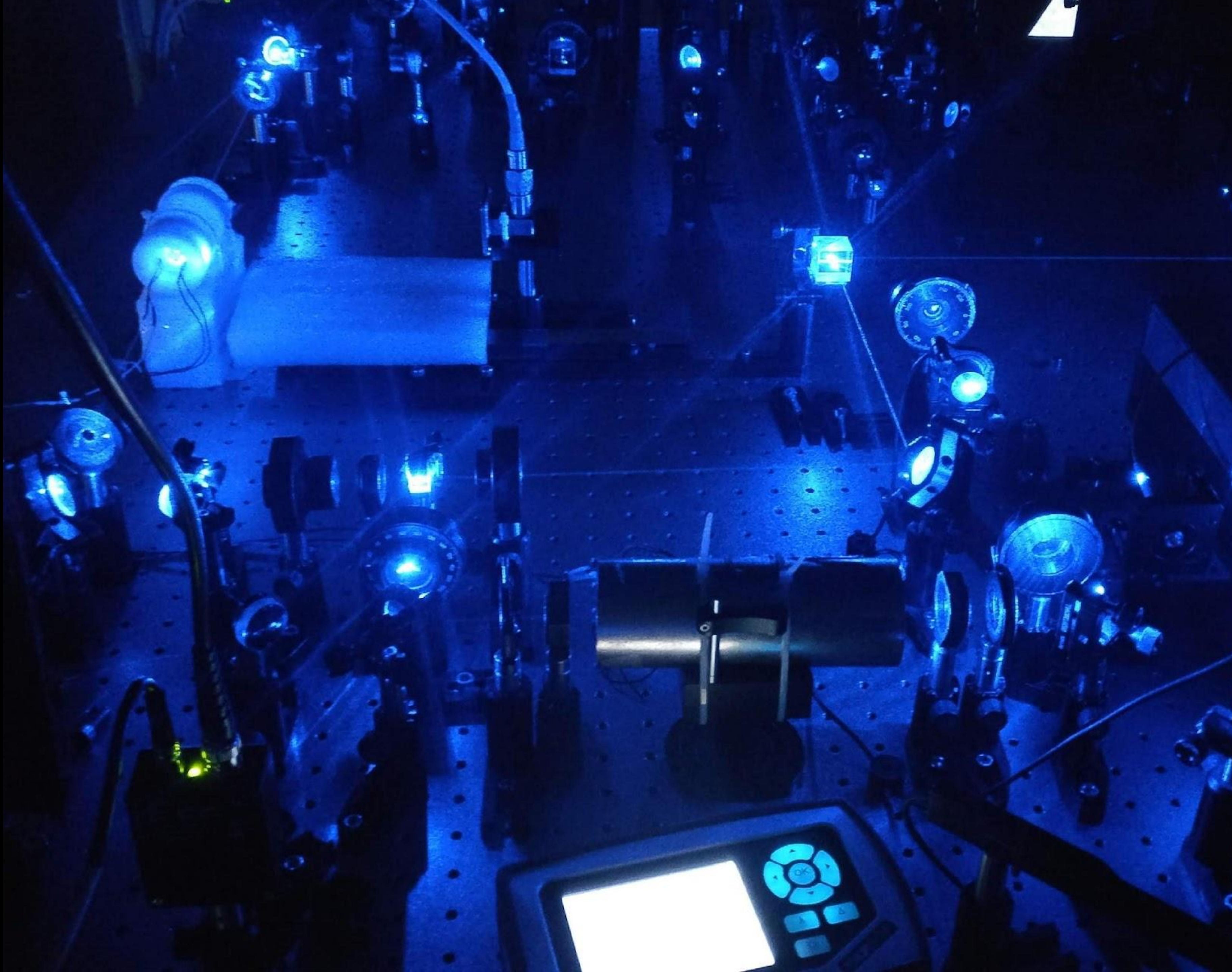
(Received 4 February 2021; revised 22 June 2021; accepted 28 June 2021; published 12 July 2021)

We present a theoretical model of a four-photon excitation process to the Rydberg state in thermal atomic vapor where the motion-induced dephasing in the system is eliminated. This is achieved by arranging the four laser beams in a suitable geometry such that the residual wave vector is reduced to zero. The method of adiabatic elimination has been used to reduce the complex five-level system to an effective three-level system to study electromagnetically induced transparency (EIT) where the transition from ground state to second excited state can be considered as the effective probe and second excited state to the Rydberg state as the effective coupling transition. The effect of the blockade phenomenon is observed in the strong interaction regime, where the two atoms are considered to be moving with independent velocities and the system is Doppler averaged using Monte Carlo simulation technique. Also, the dephasing mechanisms in the system are investigated in detail. Though the system is not frozen during the excitation process, a strong blockade effect is still observed similar to the cold atom system. We conclude the paper with a proposal for experimentally investigating the four-photon excitation process to the Rydberg state in thermal rubidium vapor.

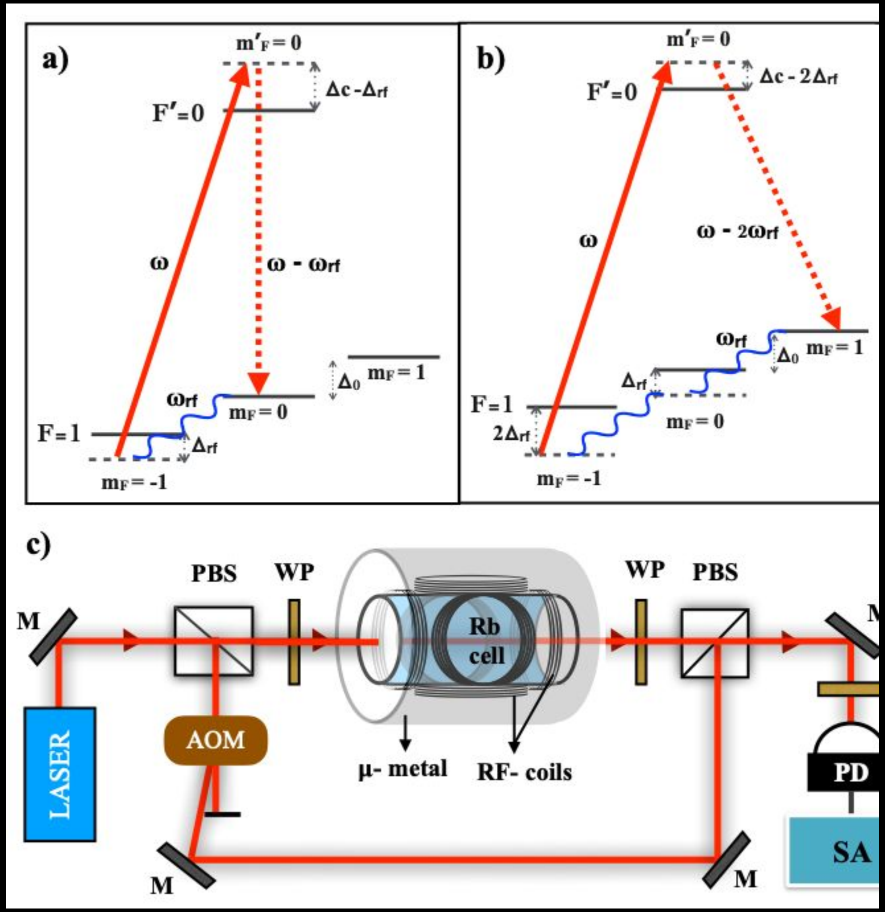
DOI: 10.1103/PhysRevA.104.013711

Sensitivity ~ -175 dBm/Hz can be achieved.
The proposed sensor has potential to surpass the fundamental limit (by standard spectrum analyzer) ~ -171 dBm/Hz.

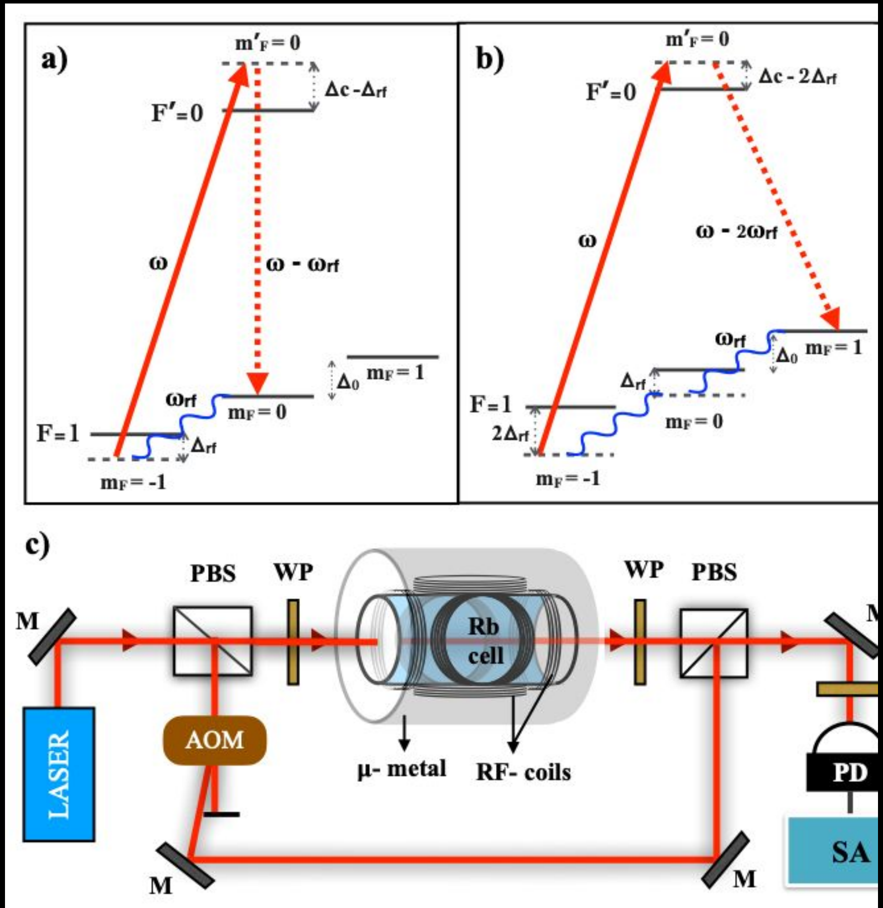
Magnetic field sensor

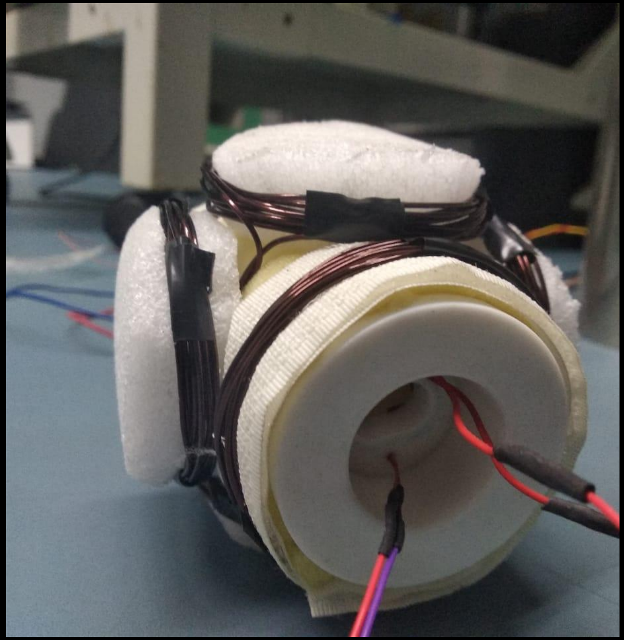


RF magnetic field induced Zeeman coherence

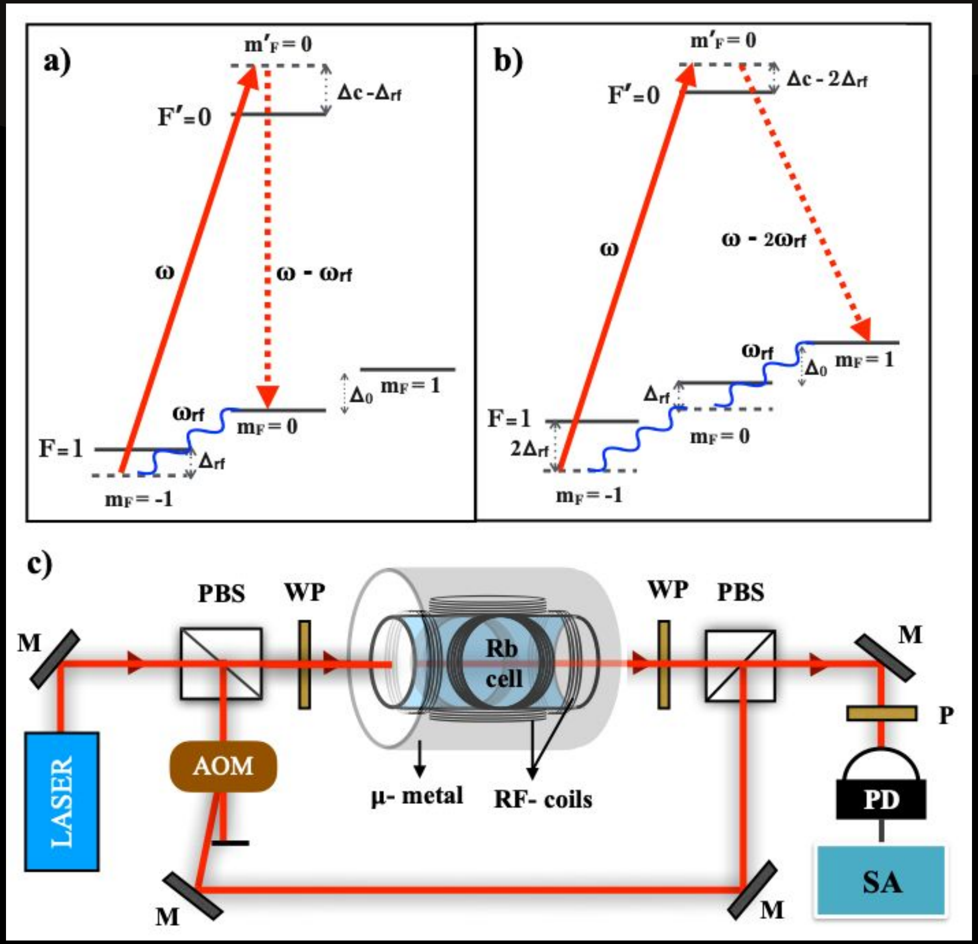


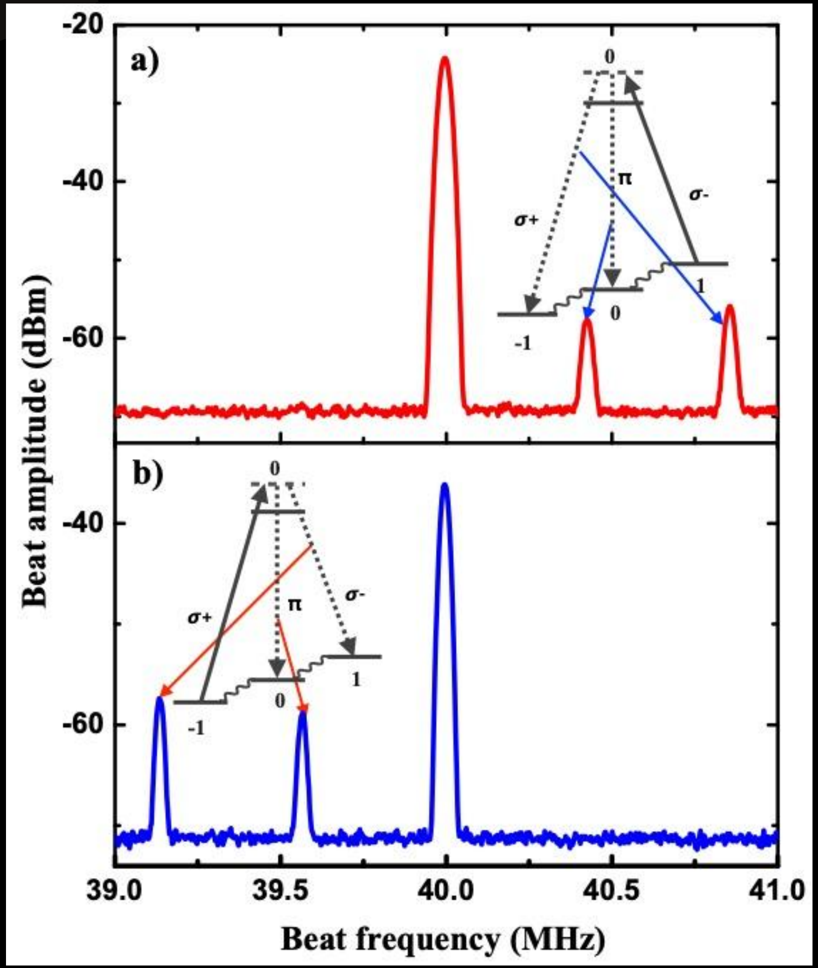
RF magnetic field induced Zeeman coherence



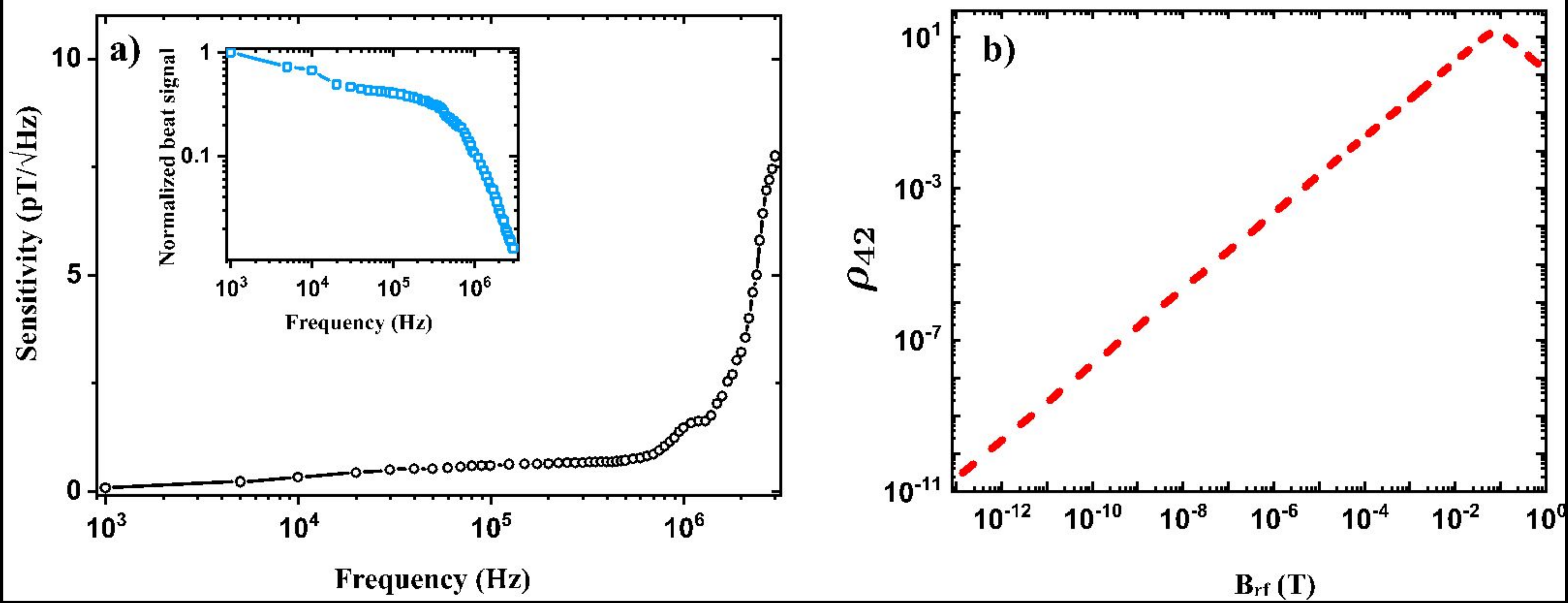


RF magnetic field induced Zeeman coherence





Sensitivity and dynamic range of the magnetometer



1) Sensitivity ~ 70 fT/Sqrt(Hz) 2) Dynamic range ~ 10^{12}

3) Arbitrary frequency resolution (limited by the measurement devices)

Cold atom set up for sensitive magnetometer

Cold atom for sensitive magnetometer

T ~ 10 μK

Acknowledgements

Acknowledgements

Thank you